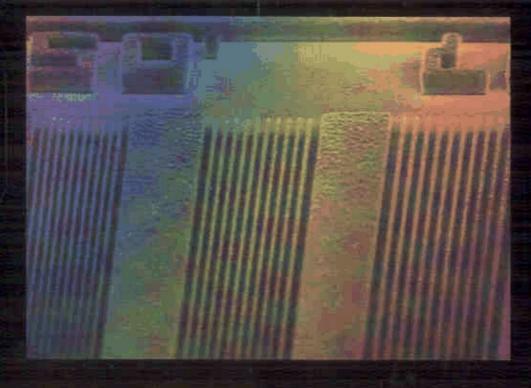
SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION

Principles and Applications



DAVID ATTWOOD

Contents

CHAPTER 1. INTRODUCTION 1.1 The Soft X-Ray and Extreme Ultraviolet Regions of the Electromagnetic Spectrum 1.2 Basic Absorption and Emission Processes 1.3 Atomic Energy Levels and Allowed Transitions 1.4 Scattering, Diffraction, and Refraction of Electromagnetic Radiation References Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom References	1 1 5 10 18 21 23
1.1 The Soft X-Ray and Extreme Ultraviolet Regions of the Electromagnetic Spectrum 1.2 Basic Absorption and Emission Processes 1.3 Atomic Energy Levels and Allowed Transitions 1.4 Scattering, Diffraction, and Refraction of Electromagnetic Radiation References Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	1 5 10 18 21
Spectrum 1.2 Basic Absorption and Emission Processes 1.3 Atomic Energy Levels and Allowed Transitions 1.4 Scattering, Diffraction, and Refraction of Electromagnetic Radiation References Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	5 10 18 21
1.3 Atomic Energy Levels and Allowed Transitions 1.4 Scattering, Diffraction, and Refraction of Electromagnetic Radiation References Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT	10 18 21
1.4 Scattering, Diffraction, and Refraction of Electromagnetic Radiation References Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT	18 21
References Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	21
Homework Problems CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	
CHAPTER 2. RADIATION AND SCATTERING AT EUV AND SOFT X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	23
X-RAY WAVELENGTHS 2.1 Maxwell's Equations and the Wave Equation 2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	
2.2 Calculating Scattered Fields 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom	24
 2.3 Radiated Power and Poynting's Theorem 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom 	24
 2.4 Scattering Cross Sections 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom 	27
 2.5 Scattering by a Free Electron 2.6 Scattering by Bound Electrons 2.7 Scattering by a Multi-electron Atom 	33
2.6 Scattering by Bound Electrons2.7 Scattering by a Multi-electron Atom	38
2.7 Scattering by a Multi-electron Atom	39
	41
References	44
	53
Homework Problems	54
CHAPTER 3. WAVE PROPAGATION AND REFRACTIVE INDEX AT EUV AND SOFT X-RAY WAVELENGTHS	55
3.1 The Wave Equation and Refractive Index	56
3.2 Phase Variation and Absorption of Propagating Waves	61
3.3 Reflection and Refraction at an Interface	66
3.4 Total External Reflection of Soft X-Rays and EUV Radiation	69

3.5	Reflection Coefficients at an Interface	71			
	3.5.1 E ₀ Perpendicular to the Plane of Incidence	71			
	3.5.2 \mathbf{E}_0 Parallel to the Plane of Incidence	77			
3.6	Brewster's Angle	80			
3.7	Field Penetration into a Lossy Medium Near the Critical Angle	82			
3.8	Determination of δ and β : The Kramers–Kronig Relations				
3.9	Applications to Glancing Incidence Optics	94			
3.10	Enhanced Reflectivity from Periodic Structures	95			
Refer	rences	96			
Home	ework Problems	97			
CHAP	TER 4. MULTILAYER INTERFERENCE COATINGS	98			
4.1	Introduction	98			
4.2	Constructive Interference of Scattered Radiation	99			
4.3	Computational Model for Calculating Reflection from a Multilayer Mirror	103			
4.4	Multilayer Fabrication	106			
4.5	Applications of Multilayer Coated Optics	107			
11.5	4.5.1 Soft X-Ray and Extreme Ultraviolet Photoemission Microscopy	10,			
	for Surface Science	108			
	4.5.2 Extreme Ultraviolet and Soft X-Ray Astronomy	108			
	4.5.3 Extreme Ultraviolet Lithography	110			
	4.5.4 Plasma Diagnostics	113			
	4.5.5 Polarization Studies of Magnetic Materials4.5.6 The X-Ray Microprobe	114 116			
n . c.	• •	119			
References Homework Problems					
Hom	ework Problems	122			
CHAP	TER 5. SYNCHROTRON RADIATION	123			
5.1	Introduction	124			
5.2	Characteristics of Bending Magnet Radiation	126			
5.3	Characteristics of Undulator Radiation	135			
	5.3.1 Undulator Radiation Pattern	137			
	5.3.2 The Central Radiation Cone	139			
5.4	Undulator Radiation: Calculations of Radiated Power, Brightness,				
	and Harmonics	141			
	5.4.1 The Undulator Equation	141			
	5.4.2 Comments on Undulator Harmonics 5.4.3 Power Radiated in the Central Radiation Cone	146 147			
	5.4.3 Power Radiated in the Central Radiation Cone5.4.4 Power as a Function of Angle and Total Radiated Power	156			
	5.4.5 Spectral Bandwidth of Undulator Radiation	161			
	5.4.6 Spectral Brightness of Undulator Radiation	165			
	5.4.7 Time Structure	168			
	5.4.8 Polarization Properties of Undulator Radiation	170			
5.5	The Scale of Harmonic Motion	172			

-	_		_	_			
r	n	ы	т	Е	ĸ	T٢	
٠.	u	ш		г	IN	1)	

ix

5.6	The Transition from Undulator to Wiggler Radiation	177			
5.7	Wiggler Power and Flux				
5.8	Femtosecond Pulse Generation	185			
References					
	ework Problems	186 188			
nom	EMOIK I LOOKering	100			
CHAP	TER 6. PHYSICS OF HOT DENSE PLASMAS	189			
6.1	Introduction	190			
6.2	Short and Long Range Interactions in Plasmas	191			
6.3	Basic Parameters for Describing a Plasma	195			
6.4	Microscopic, Kinetic, and Fluid Descriptions of a Plasma	197			
0.1	6.4.1 The Microscopic Description	197			
	6.4.2 The Kinetic Description	200			
	6.4.3 The Fluid Description	202			
	6.4.4 Plasma Expansion	211			
	6.4.5 Electron-Acoustic Waves	213			
	6.4.6 Ion-Acoustic Waves	217			
	6.4.7 Transverse Electromagnetic Waves in a Plasma	219			
	6.4.8 Resonance Absorption	227			
	6.4.9 Waves in a Magnetized Plasma	227			
	6.4.10 Non-linear Processes in a Plasma	227			
	6.4.11 Threshold for Non-linear Processes	232			
6.5	Numerical Simulations	234			
	6.5.1 Particle in Cell Simulations	234			
	6.5.2 Langrangian Zonal Calculations of Plasma Mass and Energy Transport	236			
6.6	Density Gradients: UV and EUV Probing	238			
6.7	X-Ray Emission from a Hot Dense Plasma				
0.7	6.7.1 Continuum Radiation and Blackbody Spectra	241 242			
	6.7.2 Line Emission and Ionization Bottlenecks	246			
	6.7.3 Sub-kilovolt Line and Continuum Emissions	248			
	6.7.4 Multi-kilovolt Line Emission	254			
	6.7.5 Suprathermal X-Rays	256			
	6.7.6 Laser Wavelength Trends	257			
6.8	High Harmonic Generation with Femtosecond Laser Pulses	259			
References					
Hom	nework Problems	266			
СНУЬ	TER 7. EXTREME ULTRAVIOLET AND SOFT X-RAY LASERS	267			
7.1	Basic Processes	268			
7.2	Gain	274			
7.3	Recombination Lasing with Hydrogen-like Carbon Ions	279			
7.4	Collisionally Pumped Neon-like and Nickel-like Lasers	283			
7.5	· -	291			
1.0	Compact EUV Lasers	491			

References		295
Homework Problems		299
CHAP1	TER 8. COHERENCE AT SHORT WAVELENGTHS	300
8.1	Concepts of Spatial and Temporal Coherence	301
8.2	Examples of Experiments that Require Coherence	306
8.3	Spatial and Spectral Filtering	309
8.4	Spatial and Spectral Filtering of Undulator Radiation	310
8.5	Spatially Coherent EUV and Soft X-Ray Lasers	318
8.6	The Van Cittert–Zernike Theorem	321
8.7	Examples of High Contrast Fringes Formed at Short Wavelengths	330
Refer	rences	333
Home	ework Problems	336
CHAP'	TER 9. SOFT X-RAY MICROSCOPY WITH DIFFRACTIVE OPTICS	337
9.1	Introduction	338
9.2	The Fresnel Zone Plate Lens	342
9.3	Diffraction of Radiation by Pinhole Apertures and Zone Plates	349
	9.3.1 Pinhole Aperture	351
	9.3.2 Zone Plate	353
9,4	Spatial Resolution of a Zone Plate Lens	357
9.5	Depth of Focus and Spectral Bandwidth	361
9,6	Spatial Resolution Beyond the Rayleigh Limit: The Effective Angular Illumination Profile	363
9.7	High Resolution Soft X-Ray Microscopy	365
	9.7.1 The Soft X-Ray Microscope	366
	9.7.2 The Scanning Soft X-Ray Microscope	367
9.8	Applications to the Life Sciences	369
	9.8.1 Biological Applications of the Soft X-Ray Microscope9.8.2 Biological Applications of the Scanning Soft X-Ray Microscope	372 377
9.9	Applications to the Physical Sciences: Analytic Tools for Materials and	
	Surface Science at Spatial Resolutions Below 100 Nanometers	379
9.10	Zone Plate Fabrication	385
References		388
Hom	ework Problems	394
СНАР	TER 10. EXTREME ULTRAVIOLET AND X-RAY LITHOGRAPHY	395
10.1	Deep Ultraviolet (DUV) Lithography and Beyond	396
10.2	Extreme Ultraviolet (EUV) Lithography	404
10.3	X-Ray Proximity Lithography	408
Refe	rences	412
Homework Problems		416

		CONTENTS	
APPENDIX A. UNITS AND PHYSICAL CONSTANTS			
A .1	The International System of Units (SI)	417	
A.2	Physical Constants	419	
Refe	erences	419	
APPI	ENDIX B. ELECTRON BINDING ENERGIES, PRINCIPAL K- AND L-SHELL EMISSION LINES, AND AUGER ELECTRON ENERGIES		
Dofe	erences	420	
Kere	Actices	427	
APPE	NDIX C. ATOMIC SCATTERING FACTORS, ATOMIC ABSORPTION COEFFICIENTS,		
	AND SUBSHELL PHOTOIONIZATION CROSS-SECTIONS	428	
Refe	rences	439	
APPE	NDIX D. MATHEMATICAL AND VECTOR RELATIONSHIPS	440	
D.1	Vector and Tensor Formulas	440	
D.2	Series Expansions	441	
D.3	Trigonometric Relationships	442	
D.4	Definite Integrals	443	
D.5	Functions of a Complex Variable	444	
D.6	Fourier Transforms	447	
D.7	The Dirac Delta Function	447	
D.8	The Cauchy Principal Value Theorem	447	
References		448	
APPE	NDIX E. SOME INTEGRATIONS IN k , ω -space	449	
APPEI	NDIX F. LORENTZ SPACE-TIME TRANSFORMATIONS	454	
F.1	Frequency and Wavenumber Relations	456	
F.2	Angular Transformations	458	
F.3	The Lorentz Contraction of Length	460	
F.4	Time Dilation	460	
F.5	Transforming $dP'/d\Omega'$ to $dP/d\Omega$	461	

464

465

References

INDEX